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Quark deconfinement and neutrino trapping in compact stars

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We study the role played by neutrino trapping on the hadron star (HS) to quark star (QS) conversion mechanism proposed recently by Berezhiani and collaborators. We find that the nucleation of quark matter drops inside hadron matter, and therefore the conversion of a HS into a QS, is strongly inhibit by the presence of neutrinos.

I. INTRODUCTION

Nowadays it is still an open question which is the true nature of neutron stars. In a traditional picture the core of a neutron star is modeled as an uniform fluid of neutron-rich matter in equilibrium with respect to the weak interaction. Nevertheless, due to the large stellar central density new degrees of freedom such as hyperons, meson condensates or even a deconfined phase of quark matter are expected to appear in the inner core of the star [1]. The latter possibility is a consequence of the QCD, that predicts a phase transition from hadron matter to a deconfined quark phase at few times nuclear saturation density, and was realized by several researchers soon after the introduction of quarks as the fundamentals building blocks of hadrons [2].

Berezhiani *et al.* [3] have shown recently that when finite effects at the interface between the quark and the hadron phase are taken into account, pure HS (*i.e.,* without a phase of deconfined quarks), above a threshold value of the central pressure, are metastable to "decay" into a more compact star in which deconfined quark matter is present (QS). The mean-life time of the metastable star configurations is related to the time needed to form a drop of quark matter in the stellar center, and depends dramatically on the stellar central pressure. In this work, we study the role played by neutrino trapping on this conversion mechanism. The quantum nucleation of a quark matter drop inside hadron matter is briefly revised in Sec. II. Our main results are presented in Sec. III, whereas the main conclusions are given in Sec. IV.

II. QUANTUM NUCLEATION OF QUARK MATTER IN HADRON STARS

Let us consider a pure HS whose central density (pressure) is increasing due to spin-down or due to mass accretion (from a companion star or from the interstellar medium). As the central density approaches the quark deconfinement critical density, a drop of quark matter (QM) can be formed in the central region of the star. The process of formation of the drop is regulated by its quantum fluctuations in the potential well created from the difference between the energy densities of the hadron and quark phases. Keeping only the volume and the surface terms, the potential well takes the simple form

$$U(R) = \frac{4}{3}\pi n_Q(\mu_Q - \mu_H)R^3 + 4\pi\sigma R^2 \tag{1}$$

where n_Q is the quark baryon number density, μ_Q and μ_H are the quark and hadron chemical potentials at a fixed pressure P, and σ is the surface tension for the surface separating the hadron from the quark phase.

The time needed to form the drop (nucleation time) can be straightforwardly evaluated within a semiclassical approach [4] . First one computes, in the Wentzel–Kramers–Brillouin (WKB) approximation, the ground state energy E_0 and the oscillation frequency ν_0 of the drop in the potential well $U(R)$. Then, the probability of tunneling is given by

$$p_0 = exp\left[-\frac{A(E_0)}{\hbar}\right] \tag{2}$$

where A is the action under the potential barrier which in a relativistic framework reads

$$A(E) = \frac{2}{c}\int_{R_-}^{R_+} \sqrt{[2M(R)c^2 + E - U(R)][U(R) - E]}\ . \tag{3}$$

being $R_\pm$ the classical turning points and

$$M(R) = 4\pi\rho_H\left(1 - \frac{n_Q}{n_H}\right)^2 R^3 \tag{4}$$

the droplet effective mass, with ρ_H and n_H the hadron energy density and the hadron baryon number density, respectively. The nucleation time is then equal to

$$\tau = (\nu_0 p_0 N_c)^{-1}\ , \tag{5}$$

where N_c is the number of virtual centers of droplet formation in the star. A simple estimation gives $N_c \sim 10^{48}$ [4]. To describe both the hadron and the quark phases we have adopted rather common models. The hadron phase is described within the relativistic mean field approximation with standard parameters fitted to reproduce nuclear matter saturation properties [5], whereas

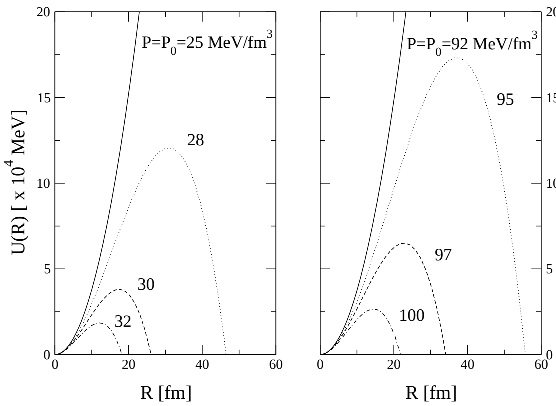

FIG. 1: Potential energy U(R) of the QM drop as a function of the radius of the drop. Left (right) panel corresponds to the neutrino free (trapped) case.

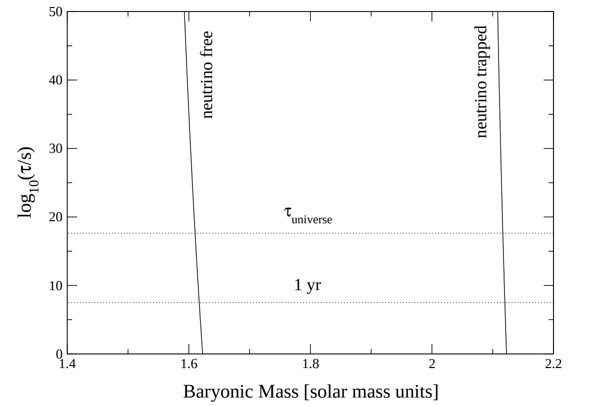

FIG. 2: Nucleation time as a function of the baryonic mass.

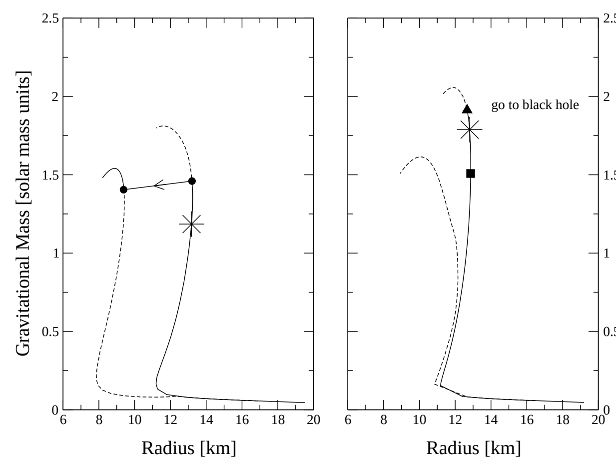

FIG. 3: Mass-radius relation for the initial HS and final QS configurations. Left (right) panel corresponds to the neutrino free (trapped) case.

for the quark phase we have adopted a phenomenological Equation of State (EoS) based on the MIT bag model for hadrons [6] with three parameters: the mass of the strange quark m_s, the so-called pressure of the vacuum B (bag constant) and the QCD structure constant α_c. In the present work, we take $m_u = m_d = 0, m_s = 150$ MeV and $\alpha_c = 0$ (see Ref. [7] for details).

III. RESULTS

To begin with we show in Fig. 1 the potential energy $U(R)$ for the formation of a QM drop for different values of the stellar central pressure above the so-called static transition point P_0 (the pressure at which the hadron and quark chemical potentials are equal). The surface tension σ is taken equal to 30 MeV/fm^2 and $B = 85.29$ MeV/fm^3. Right (left) panel corresponds to the case in which the presence of neutrinos has (not) been taken into account in the EoS of the hadron and quark phases. As expected the potential barrier is lowered as the central pressure increases. Note that the static transition point P_0 is larger when neutrinos are present, and note also that in this case, higher values of the central pressure are necessary to get a potential barrier with a height similar to the one obtained when neutrinos are absent. This means that for a given value of the central pressure the nucleation time will be much larger when neutrinos are present, and therefore, the conversion of a HS to a QS will be inhibit in this case (see Figs. 2 and 3).

The nucleation time can be plotted as a function of the baryonic mass of the HS corresponding to the given value of the central pressure, as implied by the solution of the Tolman-Oppenheimer-Volkov equations for the pure HS sequences. The results of our calculation for the two cases (neutrino free and trapped) are reported in Fig. 2 for the same values of B and σ of Fig. 1. As it can be seen from the figure a metastable HS can have a mean-life time (related to the nucleation time) many orders of magnitude larger than the age of the universe. Nevertheless, as the star accreates a small amount of mass ($\sim$ few percent of $M_\odot$), the consequential increase of the central pressure leads to a huge reduction of the nucleation time and, as a result, to a dramatic reduction of the HS mean-life time. From the discussion of the previous figure, it is clear that if neutrinos are trapped the star will need to have a much larger baryonic mass (or central pressure) than the star without neutrinos to have a comparable mean-life time. In the particular case of a star with a mean-life time $\tau = 1$ year the baryonic mass of the star with neutrinos is $M_B \sim 2.12 M_\odot$, whereas if the neutrinos have diffused out of the star $M_B \sim 1.61 M_\odot$.

Finally, in Fig. 3 we show the mass-radius (MR) relation for the initial HS and final QS sequences for the neutrino free (left panel) and neutrino trapped (right panel) cases. In both panels the configuration marked with an asterisk on the hadron MR curves represents the HS for which the central pressure is P_0. All the configu-

rations below this point correspond to absolutely stable HS ($\tau = \infty$). The full circles (triangle) on the HS and QS sequences of the neutrino free (trapped) case represent the HS for which $\tau = 1$ year and the final QS which is formed from its conversion (in the neutrino trapped case deconfinement leads to the formation of a black hole for this particular set of parameters). The square in the neutrino trapped case corresponds to the HS configuration which will evolve (assuming baryon number conservation) to the HS with $\tau = 1$ year in the neutrino free case as the neutrinos diffuse out of the star. It is clear from the figure that this and almost all the HS configurations in the neutrino trapped case will be stable with respect to the conversion.

IV. CONCLUSIONS

In the present work we have studied the role of neutrino trapping in the HS to QS conversion mechanism proposed in Ref. [3]. We have found that the quantum nucleation of a quark matter drop inside hadron matter, and therefore the conversion of a HS into a QS, is strongly inhibit by the presence of neutrinos.

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